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CORNELL UNIVERSITY
Center for Radiophysics and Space Research
ITHACA, N. Y.

A RESEARCH PROPOSAL
SUBMITTED TO THE
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

for

Renewed Support of NASA Grant NAGW-116

RADAR INVESTIGATION OF ASTEROIDS

November 1, 1981 through October 31, 1982

Principal Investigator: Prof. Steven J. Ostro

CENTER FOR RADIOPHYSICS AND SPACE RESEARCH
CORNELL UNIVERSITY

ITHACA, NEW YORK 14853

RESEARCH PROPOSAL
for
Renewed Support of NASA Grant NAGW-116

"Radar Investigation of Asteroids"

Date:	July 1981
Submitted to:	National Aeronautics and Space Administration
Submitted by:	Cornell University Ithaca, New York 14853
Principal Investigator:	Dr. Steven J. Ostro Assistant Professor Center for Radiophysics and Space Research [redacted] Tel: [607] 256-3508
Requested Period of Support:	November 1, 1981 through October 31, 1982
Total Funds Requested:	$ 45,220

Endorsements:

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Assistant Director, Office of Sponsored Programs [607] 256-5014	Peter A. Curtiss

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ABSTRACT

This is a proposal to conduct radar investigations of selected minor planets, including (i) observations during 1981-82 of 10 potential targets (2 Pallas, 8 Flora, 12 Victoria, 15 Eunomia, 19 Fortuna, 22 Kalliope, 132 Aethra, 219 Thusnelda, 433 Eros, and 2100 Ra-Shalom), and (ii) continued analyses of observational data obtained during 1980-81 for 10 other asteroids (4 Vesta, 7 Iris, 16 Psyche, 75 Eurydike, 97 Klotho, 216 Kleopatra, 1685 Toro, 1862 Apollo, 1865 Cerberus, and 1915 Quetzalcoatl). The primary scientific objectives include estimation of echo strength, polarization, spectral shape, spectral bandwidth, and Doppler shift. These measurements yield estimates of target size, shape, and spin vector; place constraints on topography, morphology, and composition of the planetary surface; yield refined estimates of target orbital parameters; and can reveal the presence of asteroidal satellites.

This proposal is for a period of one year and is for renewal of NASA Grant NAGW-116.

INTRODUCTION AND SUMMARY OF CURRENT RESEARCH

Recent efforts to apply the Arecibo Observatory's S-band radar system to investigation of minor planets have met with considerable success. During the nine months from July 1980 to March 1981, strong radar echoes were obtained from the seven asteroids: 7 Iris, 16 Psyche, 4 Vesta, 97 Klotho, 1685 Toro, 1862 Apollo, and 1915 Quetzalcoatl. Observations of three other asteroids (1865 Cerberus, 75 Eurydike, and 216 Kleopatra) did not result in firm detections, but will yield useful upper limits on these objects' radar cross sections. In contrast with these results, only six minor planets had been detected during the period 1968-1979. Table I summarizes the history and scientific highlights of asteroid radar astronomy. At present, asteroids comprise 11 of the 21 extraterrestrial targets detected with groundbased radar.

The following recent results illustrate the various types of contributions that radar investigations can make to asteroid science:

Orbital parameters

Time resolution of echoes from Iris and Apollo permitted measurements of the distances to these objects at an accuracy of one part in 10^8. The value of such measurements lies partially in their dramatic improvement in our knowledge of the targets' orbits: Predictions of Apollo's position from half a century of optical observations were shown to be several thousand kilometers in error.

TABLE 1. ASTEROIDS DETECTED WITH RADAR

Target	Date	Investigators	λ	Pol'n*	Comments
1566 Icarus	1968	Goldstein	12.6 cm	OC	First asteroid detected with radar
1685 Toro	1972	Goldstein, Holdridge, Lieske	12.6 cm	OC	
433 Eros	1975	Jurgens, Goldstein	3.5 cm	OC, SC	First precise circular polarization ratio
			12.6 cm	OC, SC	
		Campbell, Pettengill, Shapiro	70 cm	OC	First radar distance to an asteroid (6 km resolution)
1580 Betulia	1976	Pettengill, Ostro, Shapiro, Campbell	12.6 cm	OC	
1 Ceres	1977	Ostro, Pettengill, Shapiro, Campbell	12.6 cm	OC	First mainbelt asteroid detected with radar
4 Vesta	1979	Ostro, Campbell, Pettengill, Shapiro	12.6 cm	OC	Marginal detection
1685 Toro	1980	Ostro, Campbell, Shapiro	12.6 cm	OC, SC	First precise λ12.6 cm circular polarization ratio First full λ12.6 cm radar "lightcurve"

TABLE 1 (continued)

Target	Date	Investigators		Pol'n*	Comments
7 Iris	1980	Ostro, Campbell, Shapiro	12.6 cm	OC, SC	First radar distance to a mainbelt asteroid First delay resolution of asteroid radar echoes First dual-polarization radar observation of a mainbelt asteroid
1862 Apollo	1980	"	"	OC, SC	First delay-doppler map of an asteroid First distance measurements with sub-kilometer resolution
16 Psyche	1980	"	"	OC, SC	First M-type asteroid detected with radar
97 Klotho	1981	"	"	OC	
1915 Quetzalcoatl	1981	"	"	OC, SC	Smallest extraterrestrial object detected with radar
4 Vesta	1981	Ostro, Campbell, Shapiro	12.6 cm	OC, SC	

* Here SC and OC denote reception in the same sense of circular polarization as transmitted and the opposite sense, respectively.

Rotations

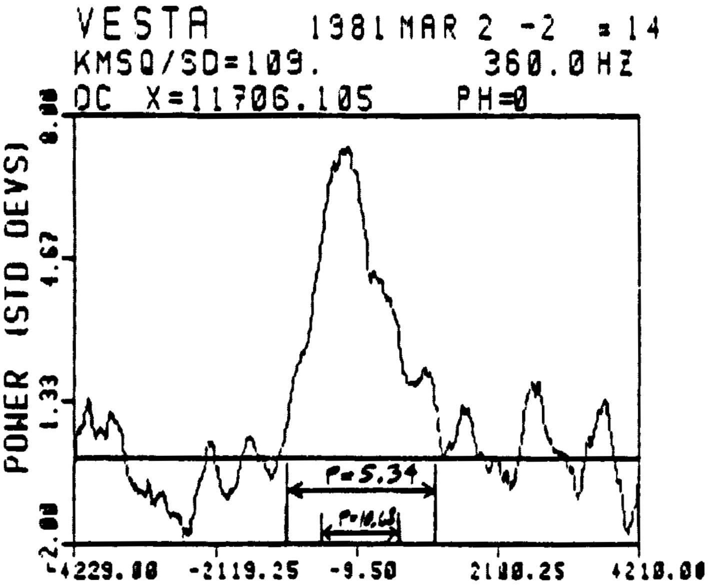
Any strong CW radar detection yields an estimate of the target's limb-to-limb bandwidth: $B = (8\pi a \sin \delta)/\lambda P$, where *a* is the mean radius, *P* is the rotation period, and δ is the "aspect angle" between the target's rotation pole and the radar line of sight. Estimation of any one of the three quantities *a*, *P*, and δ requires knowledge of the remaining two. For Vesta, whose radius is well known and whose pole direction is known to about 10°, the rotation period has been debated for several decades. The recent measurement of Vesta's power spectrum (Fig. 1a) has resolved this controversy. For Psyche (Fig. 1b), whose rotation period and mean radius are well known, the radar estimate of echo bandwidth requires that the rotation pole direction was $\sim$ 30° from the radar line of sight.

Size and shape

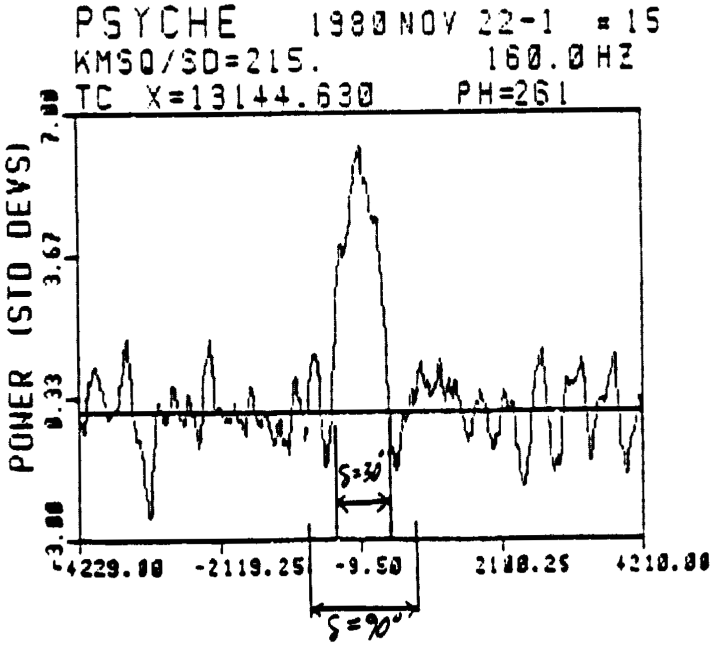
Figure 2 shows delay-doppler resolution of an echo from Apollo. The apparent dispersion of echo in time and frequency suggests that Apollo's equatorial radii span the range from about 700 m to about 800 m, and that Apollo's shape is more complex than, say, an ellipsoid. The distributions in delay and doppler of echoes from Iris suggest that this asteroid's mean equatorial radius is about three times larger than its polar radius.

Surface structure

Unlike the Moon and inner planets, the asteroids observed so far are not quasispecular scatterers of 12.6-cm-wavelength



(a)



(b)

FIGURE 1. Measurements of echo spectral bandwidth, $B = (8\pi a \sin \delta)/\lambda P$, where $\underline{a}$ is radius, $\underline{P}$ is rotation period, and δ is aspect angle. The radii of Vesta and Psyche are well known. (a) A priori knowledge of Vesta's pole position permits deduction of the rotation period, 5.34 hours. (b) A priori knowledge of Psyche's period constrains the aspect angle to $\sim 30°$.

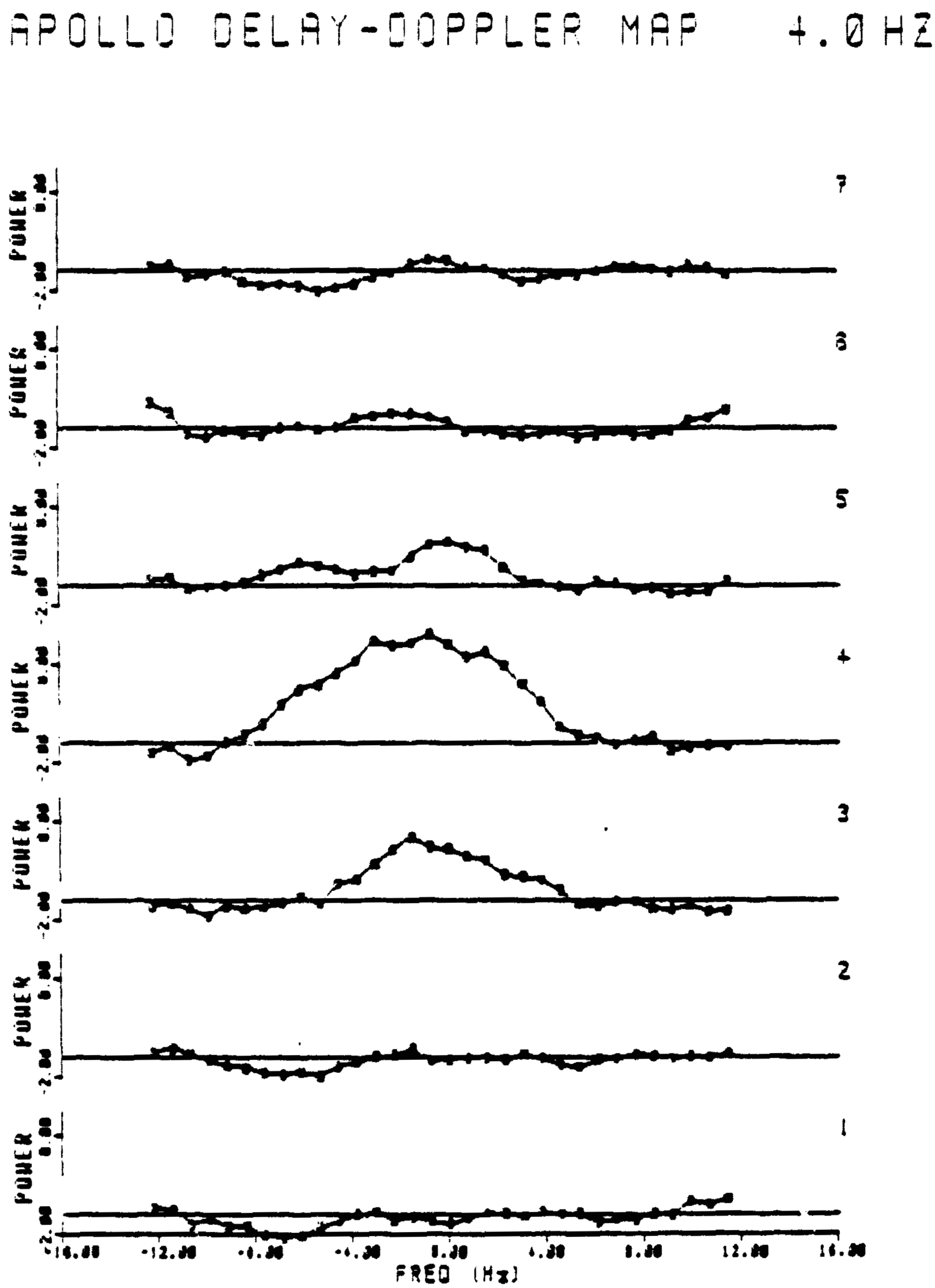


FIGURE 2. Delay-doppler resolution of radar echoes from Apollo. Power spectra are plotted at seven delays separated by 5 μs (750 m). Delay #1 is closest to the radar. Since the delay resolution is 10 μs, spectra in adjacent range boxes are correlated. Spectral resolution is 0.8 Hz.

radar waves. Although regoliths may be present on asteroidal surfaces, large, smooth areas characterized by small rms slopes cannot be morphologically dominant.

Values of the circular polarization ratio, μ_C, of SC echo power to OC power, measured for the Earth-crossing asteroids Apollo, Quetzalcoatl, and Toro, average about 0.26. This number is higher than that for the Moon ($\mu_C \sim 0.1$) but lower than that for the diffuse component of the lunar echo ($\mu_C \sim 0.5$). It is much lower than the value (~ 1) expected for complete depolarization by small-scale roughness and/or multiple scattering. No mainbelt asteroid has been detected in the SC polarization, but the dual-polarization observations of Iris, Psyche, and Vesta require that μ_C be no greater than, and perhaps much less than, 0.3. As a class of targets, the asteroids seem to be smooth at decimeter scales but very rough at some scale(s) longer than a few meters.

Composition

Optical and infrared reflection spectra show that M-type asteroids such as Psyche have free Fe/Ni metal on their surfaces. If these objects are made entirely of metal, they are probably remnants of the cores of much larger objects which differentiated and cooled before they were fragmented in collisions. However, optical and infrared observations are insensitive to subsurface composition, and cannot distinguish free metal from a mixture of free metal and neutral silicates. Psyche's radar albedo is the highest measured for any asteroid to date, but is much lower than that expected for a pure metallic object.

DESCRIPTION OF THE PROPOSED RESEARCH

Observations

Support is requested to conduct radar observations of asteroids 2 Pallas, 8 Flora, 12 Victoria, 15 Eunomia, 19 Fortuna, 22 Kalliope, 132 Aethra, 219 Thusnelda, 433 Eros, and 2100 Ra-Shalom. Eros in the only one of these potential targets previously detected by radar (Jurgens and Goldstein, 1976; Campbell et al., 1976). Eros' 12.6 cm radar properties are not well known. Practically nothing is known about the physical properties of either Ra-Shalom (an Aten asteroid with the smallest known orbital semimajor axis) or Aethra (the first Mars-crosser discovered). Pallas, Flora, Victoria, Eunomia, Fortuna, Kalliope, and Thusnelda are well-known main-belt asteroids. Except for Fortuna, each of these "resembles" some radar-observed asteroid in terms of surface mineralogy inferred from spectral reflectance signatures (Gaffey and McCord, 1979), and/or in terms of CSMERU taxonomic class (Zellner, 1979). Pallas appears similar to Ceres (detected by Ostro et al., 1979); Flora, Victoria, Eunomia, and Iris are S-type objects; Kalliope, Thusnelda, and Psyche are M-type objects. Fortuna is a C-type and is the first potential mainbelt radar target whose mineralogy resembles carbonaceous chondritic meteorites. Clearly, it is desirable to compare the radar properties of a large statistical sample of asteroids which seem simila on the basis of other criteria.

The proposed observations will attempt to achieve the following experimental objectives for each asteroid:

1. Detection of the target, measurement of absolute Doppler shift and measurement of absolute radar cross section.
2. Measurement of target limb-to-limb bandwidth.
3. Measurement of the disc-integrated circular polarization ratio μ_C.
4. Exploration of the dependence of radar reflectivity and polarization on rotational phase.

These objectives will be pursued using a simple CW waveform. If echo strength is sufficently high (as is expected only for Flora and Eros), phase-coded CW observations will be carried out to resolve the echoes in delay, permitting determination of target distance and direct measurement of target radius. An accurate estimate of radius, whether from radar observations or independent methods, is necessary for reliable estimation of intrinsic reflectivity (i.e., geometric albedo).

Recently reported speckle interferometry of Pallas by Hege et al. (1980) suggests the presence of a satellite about 30% as large as Pallas itself. Photoelectric observations of a stellar occultation by Pallas (Clark and Milone, 1973) may provide tenuous support for such a satellite (Clark et al., 1981). Certain lightcurve and/or stellar occultation data for various other asteroids have also been interpreted as possible evidence for binary asteroids (Van Flandern et al., 1979). Theoretical considerations do not preclude the existence of multiple asteroids, and even suggest that collisional processes may have bestowed companions on $\sim$ 10% of the main belt minor planets (Hartmann, 1979; Chapman et al., 1980). Nevertheless, while the binary-asteroid hypothesis provides an interesting, credible explanation for various peculiar observational results (Weidenschilling, 1981), this hypothesis has not been proved for any asteroid.

For Pallas, speckle interferometry by Worden and Stein (1979) yielded a diameter estimate (673 ± 55 km) at odds with the very reliable occultation value (538 ± 12 km) reported by Wasserman et al. (1979). Whether or not Pallas has a companion, there remains some uncertainty about this asteroid's configuration.

Calculations by Showalter (1981) indicate that Pallas is one of the best candidates for having a satellite that can be detected using the current Arecibo S-band radar system. Victoria's a priori signal-to-noise ratio is probably not sufficient for detection of a satellite much smaller than Victoria itself.

Signal-to-noise calculations (Ostro, 1980) show that Ra-Shalom, Flora, Eros, Pallas, Victoria, and Fortuna will be detectable in a single night (i.e., observing session). Integration over several nights will probably be necessary to detect Thusnelda, Kalliope, and Eunomia at the five-standard-deviation level. Although Aethra's radius is unknown, plausible assumptions about its optical albedo suggest that it is marginally detectable in about a week. Except for Eunomia and Fortuna, the 1981 or 1982 apparition of the proposed targets presents the most favorable opportunity for Arecibo radar observation during this decade.

Arecibo telescope time is not normally requested more than a year before the proposed observations. Time for observations of Victoria and Fortuna in October 1982 will be requested this fall. Time for observations of the other eight asteroids has already been assigned to the principal investigator.

Data analyses

Support is requested for continued analysis and interpretation of radar data obtained during 1980-81 for Toro, Apollo, Quetzalcoatl, Cerberus, Iris, Psyche, Klotho, Vesta, Eurydike, and Kleopatra. A priori predictions of echo strength are generally correct only to within an order of magnitude because of the uncertainty in the target's size, rotation rate, pole position, and/or reflectivity. Each asteroid is a unique planet and poses particular problems of observation, data analysis, and interpretation. For targets yielding echoes with high signal-to-noise ratios (e.g., Apollo), the radar data sets are enormous, and interpretation of data becomes an iterative bootstrapping operation. At the other extreme, data yielding marginal detections or non-detections (e.g., Kleopatra) must be exhaustively analyzed to ensure assignment of accurate, useful upper limits on radar cross section.

The scientific objectives of the proposed data analyses include:

1. Development of triaxial elliposidal models for Apollo, Toro, Quetzalcoatl, Iris, and Psyche. Such models are tedious to produce (because of the lack of closed-form analytic solutions for integrals encountered) but are necessary to obtain realistic estimates of limb-to-limb bandwidth and radar scattering law.
2. Analysis of Apollo's circular polarization ratio as a function of frequency over the more than 300° of rotational phase sampled by the 1981 observations. If polarization features exist, it may be possible to ascertain the location and extent of the source regions.
3. Parameterization of the radar reflectivity of metal-containing asteroid surfaces in terms of particle size, metal/silicate ratio, and density.
4. Modelling of radar spectral signatures for binary asteroid configurations.
5. Reduction of high resolution (4 us) Apollo ranging data, and generation of delay-doppler maps.
6. Improved prediction of asteroid radar signal-to-noise ratios, coupled with a search for favorable radar observing opportunities.

7. Definition and classification of the radar scattering properties of minor planets.
8. Correlation of radar and visible-wavelength properties as functions of rotational phase.

BUDGET ESTIMATE

For Renewed Support of NASA Grant NAGW-116

"Radar Investigation of Asteroids"

November 1, 1981 through October 31, 1982

	11/1/81- 6/30/82	7/1/82- 10/31/82	Total
Prof. S. Ostro, Principal Investigator 100% 2½ Mos. Summer	$ 1,276	$ 5,104	$ 6,380
Graduate Research Asst., 25% AY	4,550	1,472	6,022
100% 2½ Mos. Summer	480	1,920	2,400
Secy/Clerical, part-time	1,998	1,000	2,998
TOTAL SALARIES	$ 8,304	$ 9,496	$17,800
Indirect Costs, 72% of Salaries (through 6/30/82)	5,979	---	5,979
Fringe Benefits	640	766	1,406
Travel*	2,275	2,275	4,550
Computing (17 hrs. @ $370/hr)	4,070	2,220	6,290
Publications & Reports	1,000	500	1,500
Communications	330	170	500
Supplies & Services	670	330	1,000
Total Direct Costs		15,757	
Modified Total Direct Costs [Total Direct Costs less tuition component of graduate student costs and computer costs]		12,643	
Indirect Costs, 49% of Total Direct Costs (effective 7/1/82)		6,195	6,195
TOTAL BUDGET	$23,268	$21,952	$45,220

(*See attached explanation)

7/17/81

TRAVEL EXPLANATION

4 trips to Arecibo Observatory, P.R., duration each trip 11 days			
Air fare: 4 trips @ $550/trip		$2,200	
Living expenses: 44 days @ $16/day		704	
	Total	$2,904	
2 trips to Midwest meetings, duration each trip 4 days			
Air fare: 2 trips @ average $675/trip		$1,350	
Living expenses: 8 days @ $37/day		296	
	Total	$1,646	
	Total Travel		$4,550

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EMPLOYMENT:	Assistant Professor of Astronomy, Cornell University, 1979 to present Postdoctoral Research Associate, M.I.T., 1978-1979 Research Ceramist, Corning Glass Works, 1970-1971
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